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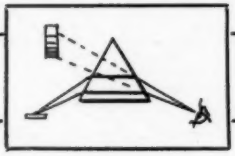

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PHOTOGRAPHIC PLATES FOR USE IN SPECTROSCOPY AND ASTRONOMY*

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[Kodak Research Laboratories, Rochester, N. Y. Received Oct. 24, 1931]

Modern spectroscopic and astronomical observation is carried on almost entirely by means of photography. The efficiency of such work is therefore dependent to a very large extent upon the quality of the photographic plates which are used and upon their suitability for the work to which they are applied. Photographic plates can be of many kinds, and a choice of the correct plate for each purpose involves a considerable amount of knowledge and careful consideration of the plates available.

This paper has been prepared for the purpose of giving specific information as to the characteristics of the plates made by the Eastman Kodak Company which are specially suitable for scientific work. In order that such information may be useful, it is necessary to name the plates, and an apology is perhaps due for the introduction of such commercial information into the proceedings of a scientific society. Unfortunately, however, generalizations on such subjects are of no value. The statement of the numerical value of the speed or resolving power of an unnamed process plate conveys no information to the reader, and

* Communication No. 487.

the only form in which such information can be of use is as related to specific and named materials.

THE SENSITOMETRIC CHARACTERISTICS OF PHOTOGRAPHIC PLATES

Photographic materials are generally said to differ in speed, in contrast, and in color sensitivity. The first two qualities are generally determined by means of the *characteristic curve*. This curve, first suggested

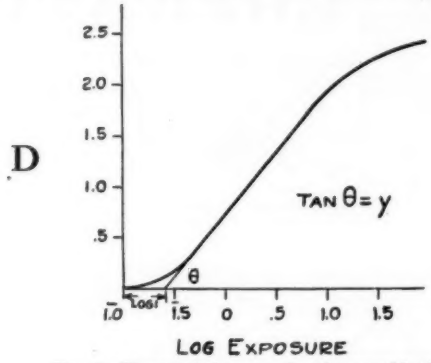

FIG. 1. *Characteristic curve of a photographic plate.*

by Hurter and Driffield in 1890, is obtained by giving the material a series of exposures and then, after development, measuring the optical densities of the silver deposits, which are plotted against the logarithms of the exposures (E). Such a curve is shown in Fig. 1. A considerable portion of this curve lies approximately along a straight line, and if this straight line be produced to cut the exposure axis at a point corresponding to the exposure i, the equation to the straight line will be

$$D=\gamma(\log E-\log i)$$

where γ is the slope of the line.

The value i was termed by Hurter and Driffield the *inertia*, and they expressed the sensitiveness of photographic materials by dividing i into a constant. The numerical value found for the inertia depends, of course, upon the quality of the light used for exposure. Hurter and Driffield used at first a standard candle and later a pentane lamp, so that their exposures are stated as *seconds of exposure to one candle power of radiation of low temperature (about 1900°K) at one meter distance.* The so-called "*H & D* speeds" were then determined by dividing the value for the inertia found as above into 34; i.e., $34/i=H \& D$ speed.

Recently, the International Congress of Photography has agreed to define the photographic unit of intensity as *one visual candle power of light of approximately sunlight quality* (defined as obtained by a filter of specified composition and corresponding to a light source of approximately 5000°K). This unit has a photographic intensity on ordinary high speed plates about six times that of the low temperature unit

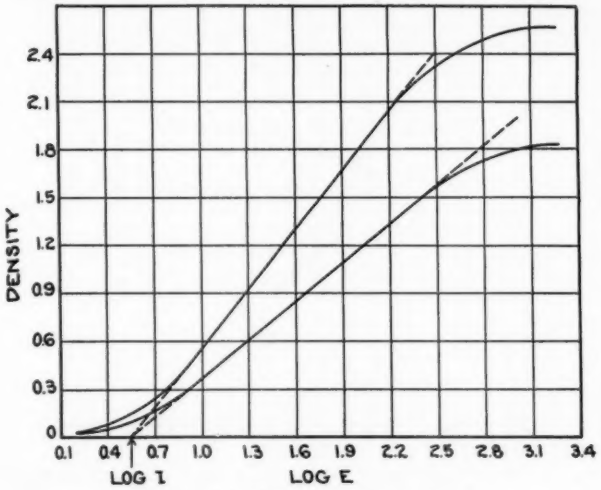

FIG. 2. *Intersection of characteristic curves.*

used originally by Hurter and Driffield and gives inertia values which are correspondingly lower.

Convenient speed numbers can be obtained by dividing these inertia values into 10. Manufacturers of photographic materials have used various light sources and various numerical constants for the conversion of inertias into speed numbers. Unfortunately, this practice has made it impossible to compare the speed numbers assigned to photographic materials by different makers. In Germany the system used for the marking of plate speeds is a modification of that due originally to Scheiner, the plates being exposed behind a rotating sector wheel and the speed expressed as that of the smallest angular opening to leave a visible trace after development, the reading thus being that of the "Schwellenwert" or threshold speed. This system also has been subject to difficulties involved in the choice of light source used, and often the numbers given have little scientific value.

When plates having sensitometric exposures impressed on them are developed for various lengths of time, the straight line portions of the characteristic curves usually intersect approximately at the inertia point (see Fig. 2), so that the differences between them can be expressed simply in terms of the numerical value of γ. If, now, the value of γ be plotted against the time of development, an exponential curve is obtained, of which an example is shown in Fig. 3. The equation of this curve is approximately that of a reaction of the first order, i.e.,

$$\gamma = \gamma_\infty (1 - e^{-kt})$$

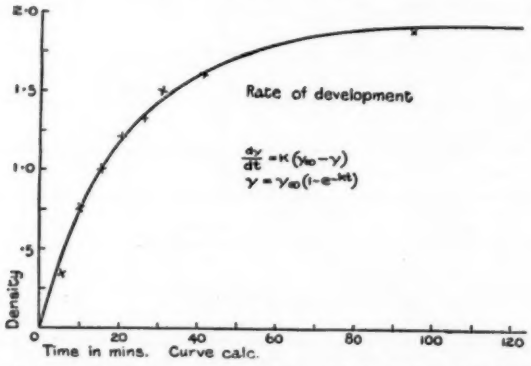

FIG. 3. *Curve showing relation of development factor to time of development.*

where γ_∞ is the value of γ obtained if development be indefinitely prolonged; i.e., it is the maximum value of γ available for that material, while k is the velocity constant of development and is dependent upon the constitution and temperature of the developer used, and t is the time of development for the value of γ under consideration. In practice it is convenient to express the contrast of a given material in terms of γ_∞ and of the γ obtained by a fixed time of development in a given developing solution.

The effective sensitiveness of a photographic material depends to a large extent upon the exact way in which it is used. Where correct tone reproduction is required, the system involving the determination of the inertia point is certainly valuable, but in astronomical photography quite a different method of expression seems more suitable.

Consider the characteristic curves of two materials, A and B, shown in Fig. 4. If the speed is measured in terms of inertia, A is a faster plate than B. This is true also if we judge sensitiveness by the exposure re-

quired to produce a minimum deposit. If, therefore, our object is to obtain a faint image with the shortest possible exposure, we should select material A. If, on the other hand, we require in the image a certain minimum density in order to make satisfactory readings on the plate and suppose this density to be a value above that of the intersection point of the two curves—then, *for that purpose*, B is a faster material than A. According to Mr. T. Dunham,[1] Jr., "In photographing stellar spectra what is required is a certain minimum density of about 0.6, which is adequate for the detection and measurement of weak absorp-

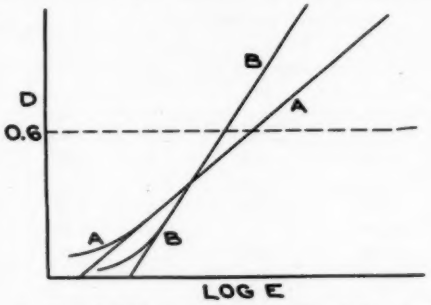

FIG. 4. *Characteristic curves illustrating the relative speeds of two materials.*

tion lines." Naturally, the determination of the exposure required to produce a given density involves a decision as to the γ which it is practicable to reach in development. Consideration of this question seems to indicate that in practice the maximum γ to which plates can be developed as a routine with a minimum of fog may be taken as 80 percent of γ_∞. Accepting Dunham's criterion, then, we may define the astronomical sensitiveness S_A as inversely proportional to the exposure expressed in seconds at one meter to one candle power of the international high temperature standard light source which will produce a density of 0.6 when the material is developed until γ reaches a value 0.8 γ_∞. In the following table are given the inertias, $10/i$ speeds and S_A values of average batches of those plates made by the Eastman Kodak Company which are chiefly used by astronomers.

In astronomical photography the phenomenon known as "the failure of the reciprocity law" is of great importance. The reciprocity law as enunciated for photochemical reactions by Bunsen and Roscoe states

[1] *The Application of Photography to Astrophysics*, presented at the VIIIth International Congress of Photography, Dresden, 1931.

that "the product of a photochemical reaction is dependent simply on the total energy employed;" that is to say, on Intensity × Time, and is independent of the two factors separately. This was shown by Abney not to be true for photographic materials and the matter was investigated quantitatively by Schwarzschild and others. With the long exposures necessary in astronomy, the failure of the reciprocity law assumes very large proportions and is therefore an important factor in

TABLE 1.

Material	6 mins. development in D-11 at 65°F.			D-11 at 65°F.		
	Inertia (i)	$10/i$	γ	γ_∞	S_A*	$T_d(0.8\gamma_\infty)$
Eastman Process	0.25 mcs	40	3.30	3.70	2.5	4.0 mins.
" 33	0.036	275	1.50	1.90	11.0	6.0
" 36	0.022	450	1.30	1.60	15.0	6.0
" 40	0.017	575	1.20	1.50	18.0	6.0
" Speedway	0.014	700	1.00	1.40	20.0	6.4
Wratten M	0.050	200	3.10	3.80	12.0	6.0
" Pan.	0.025	400	2.10	2.80	21.0	6.5
" Hyper Pan.	0.013	800	1.60	2.20	33.0	7.0

* $S_A = 1/E$ when E = exposure in mcs. of daylight required to produce a density of 0.60 above fog when developed in D-11 at 65°F. to a contrast equal to $0.8\gamma_\infty$.

controlling the choice of materials, especially in photographic photometry.

According to Schwarzschild, the effect of a photographic exposure (E_{ef}) can be expressed approximately in terms of the equation

$$E_{ef} = It^p$$

where I is the intensity and t the time of exposure and p is a constant. The matter was investigated later by Kron, who found an equation of a catenary type to hold, the value of p not being constant but varying continuously with the intensity, and this result has been confirmed by Huse, Jones and Hall, and others.[2]

Reciprocity curves for a few materials in this paper are given in Fig. 5, which shows the effective exposure required to obtain a given density plotted against the intensity. It will be seen that these are distinguished

[2] E. Huse, L. A. Jones, and V. C. Hall. *On the Relation between Time and Intensity in Photographic Exposure*, J.O.S.A., *7*, 1107; 1923: *11*, 319; 1925: *12*, 321; 1926: *13*, 443; 1926.

by a minimum corresponding to an optimum value of the intensity, this being the intensity at which the greatest effect is produced for a given product of It. The reason that Schwarzschild obtained his result is that he was an astronomer working in the region on the low side of optimum intensity with exposures varying from a few minutes to several hours, so that Schwarzschild's simple expression could be applied throughout a limited range.

For photometric work the reciprocity failure makes it desirable and almost necessary that the comparison exposures should be for the same

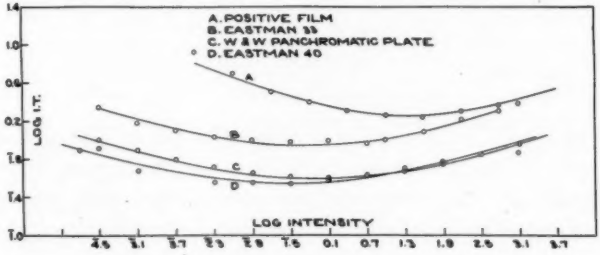

FIG. 5. *Reciprocity curves for materials.*

time as that of the object to be measured, so that the unknown intensity can be interpolated on a scale of known intensities, the times of exposure being the same.

In addition to their sensitometric characteristics, photographic materials differ in two important physical properties—their resolving power and their graininess. The resolving power of a photographic material is conditioned by two factors—the turbidity of the emulsion and the contrast. The turbidity is dependent also upon two factors—the light scattering power of the emulsion and its absorption. The spread of an image with increase of exposure is a direct measure of the turbidity. It is well known that if the geometric image of a point or an extremely narrow line upon a photographic plate be given an increasing series of exposures, the diameter, d, of the image will increase in accordance with the equation:

$$d = a + b \log E$$

where a and b are constants.

This property is, of course, used for the photometry of stellar magnitudes by the measurement of the diameter of the star image. But, whereas the equation given holds in the laboratory through a con-

siderable range of exposures, astronomical observations in general appear to be better satisfied by modifications of this formula.[3] The constant b may be taken as a measure of the turbidity of the emulsion and has been termed by Ross the "astrogamma." The contrast of the image

TABLE 2. *Resolving power for optimal image density; exposing radiation, incandescent tungsten at 3000° K.*

Test object contrast	R.P. ($\gamma=0.8\gamma_\infty$)
1.6	22
3.2	32
6.3	39
25.0	46
1000.0	51

is, of course, measured by the development factor, γ, although it must be remembered that the development factor at the edge of an image is very different from that which is obtained by direct sensitometric measurement of comparatively large areas owing to the diffusion and chemi-

TABLE 3. *Resolving power; Test object contrast = 1000; exposing radiation, incandescent tungsten 3000° K.*

Image density	R.P. ($\gamma=0.8\gamma_\infty$)
0.2	6
0.6	36
1.0	46
1.6	48
2.6	35

cal effects produced by the rapid variation in concentration of the developing solution.

In addition to the factors dependent directly upon the structure of the photographic material itself, the resolving power will vary with the contrast of the optical image and with the density produced, as well as with the quality of the exposing radiation. Thus, the variation of resolving power with the contrast of the object is shown in Table 2, and its variation with the optical density of the image is shown in Table 3, the figures being averages of measurements on several materials.

[3] See F. E. Ross, *The Physics of the Developed Photographic Image*, Monographs on the Theory of Photography, from the Research Laboratory of the Eastman Kodak Company, published by the D. Van Nostrand Co., 1924.

The variation with wave length for the Wratten *M* plate is shown in Fig. 6. In practice, the resolving power is best measured by a series of photographs of line gratings. The average resolving powers of the ma-

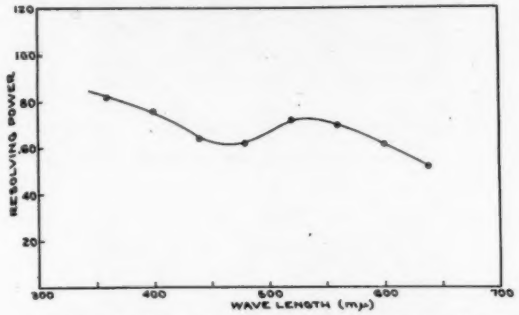

FIG. 6. *Variation of resolving power with wave length.*

terials under consideration are given below for an optical image contrast of 20 and for the density for which the resolving power is a maximum when the development γ is 0.8 γ_∞:

TABLE IV. *Resolving power values for optimal image density; test object contrast = 20; $\gamma = 0.8\gamma_\infty$; white light = incandescent tungsten at 3000° K.*

Material	R. P. (γ=440 mμ)	R. P. (white light)
Eastman process	80	80
Eastman 33	60	60
Eastman 36	38	38
Eastman 40	40	40
Eastman Speedway	35	38
Wratten M plate	65	68
Wratten Pan.	40	45
Wratten Hyper. Pan.	38	42

The granular structure of a photographic image is, of course, a factor of great importance. It influences very largely the accuracy of measurements both in the determination of stellar positions and of the position of absorption lines in spectroscopy.

Fig. 7, due to Dunham, shows enlargements of the region of the λ425 mμ iron lines photographed with a stellar spectrograph, using above the Eastman Process plate and below the Eastman 40.

Dunham has suggested[4] that the relative graininess of plates can be

[4] *loc. cit.*

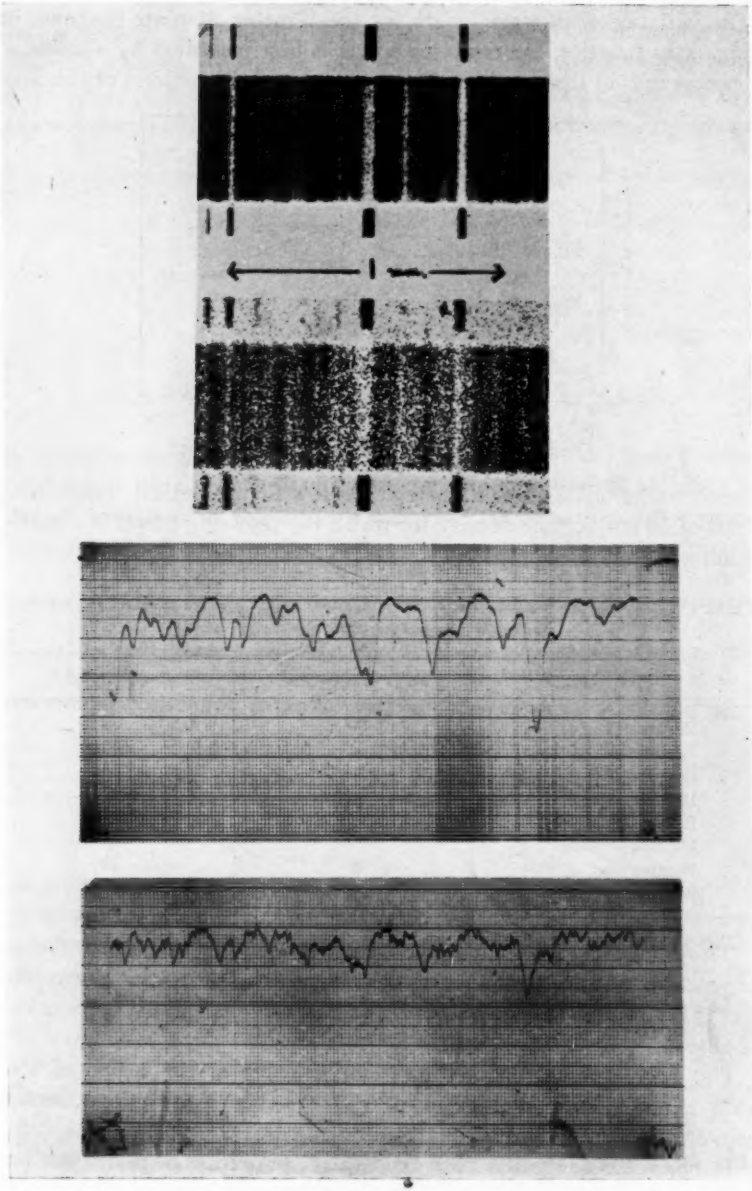

FIG. 7. *Enlargements of photographs of iron lines together with microdensitometer tracings.*

shown very easily by microphotometer tracings of regions uniformly blackened to a density of 0.3. These are shown in Fig. 8 for the plates mentioned, the slit of the microphotometer being 0.5 mm in length and

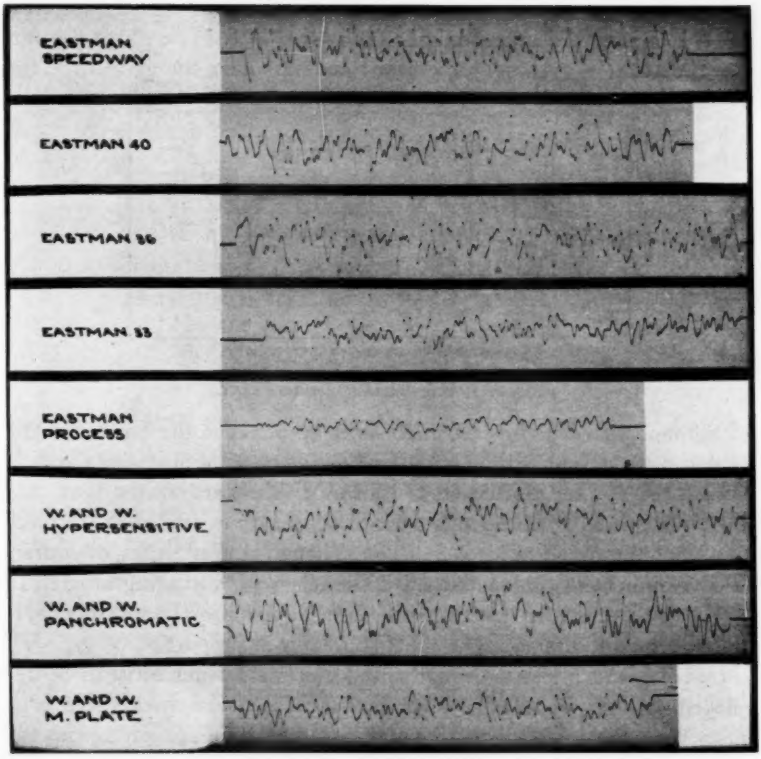

FIG. 8. *Microdensitometer tracings showing the graininess of materials.*

5 microns wide, a customary setting in astronomical work. The graininess may be expressed numerically in terms of average deviation from the main line, the unit being 1/1000 of the total deviation from clear film to the maximum density.

In addition to these effects, due to the photographic material itself, one of the most troublesome factors in photometric work is the Eberhard effect, especially when large variations in intensity occur within the small part of a millimeter, as is the case in stellar spectra. The Eber-

hard effect is undoubtedly due to local differences in the concentration of developers, the developer becoming exhausted locally where development is most active and accumulating reaction products which restrain its action.

Fig. 9, due to Dunham, shows at the left how an artificial spectral line which should descend only as far as the dotted line drops too far. A wider band of rectangular contour has dips near the end, while the

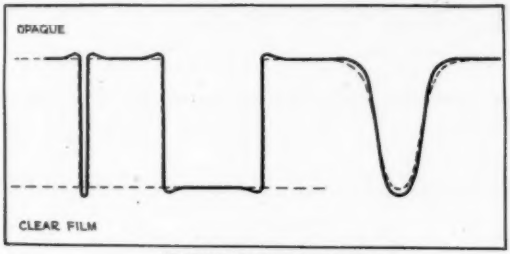

FIG. 9. *Drawing showing Eberhard effect.*

background density rises too high as it approaches the band. At the right the effect is shown on a stellar line whose true intensity curve is represented by the dotted line. Professor Eberhard states that this effect disappears when ferrous oxalate developer is used, but we have been unable to confirm his conclusion. The effect diminishes, of course, as development is prolonged and approaches γ_∞, vanishing altogether at γ_∞, since then the whole image is developed and the retarded portions catch up to the rest. The effect is greater in proportion to $(\gamma_\infty - \gamma)$, so that it is much less with high speed materials which have to be developed to high γ's relative to the value of γ_∞ than with more contrasty materials, for which too high a γ may be disadvantageous for other reasons. The effect can undoubtedly be diminished considerably by brushing the image during development with a soft camel's hair brush, a procedure which is advantageous in many other ways, notably in assuring uniformity of development. For all photometric work brush development should be employed.

DESCRIPTION OF THE VARIOUS TYPES OF MATERIALS SUITABLE FOR SPECTROSCOPIC AND ASTRONOMICAL PHOTOGRAPHY

SECTION I

Materials for the Photography of the Ultraviolet. When the ultraviolet region of the spectrum below $\lambda 250$ mμ is photographed, the absorption

by the gelatine becomes important, gelatine having a strong absorption for ultraviolet light below λ280 mμ and absorbing practically all radiation below λ200 mμ even in very thin layers. Fig. 10 shows the way in which the ultraviolet spectrum falls off in intensity when photographed on an ordinary plate owing to absorption of the gelatine.

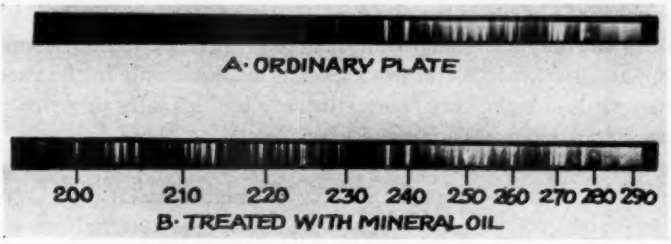

FIG. 10. *Photograph of the ultraviolet spectrum on ordinary and sensitized plates.*

Schumann, when studying the extreme ultraviolet spectrum, worked out a method of making plates which would be sensitive to the very short waves. These plates were either entirely free from gelatine or contained only a small trace of gelatine to bind the silver bromide together.[5] These plates are difficult to make and have to be prepared individually by hand. They are consequently very expensive.

Duclaux and Jeantet[6] describe two other means of photographing the extreme ultraviolet, one by treating an ordinary plate with sulfuric acid so as to dissolve the gelatine, and the second by bathing the plate with fluorescent materials, such as mineral oils, which transform the short waves into longer ones that can penetrate the gelatine. In the last few years, this method has been applied generally with success, Lyman having used plates treated in this way down to λ58 mμ in the extreme ultraviolet. Various oils give results which differ somewhat in different workers' hands, and this aspect of the subject, together with the use of a fluorescent oil for photometry, has been investigated by Harrison.[7]

As a result of an investigation of the fluorescence of a large number of organic substances when exposed to ultraviolet light, Mr. R. E. Bur-

[5] For a description of Schumann's method, see Baly, *Spectroscopy*, p. 359.

[6] J. Duclaux and P. Jeantet, *Plaques Photographiques pour l'Ultraviolet Extreme*, J. de Physique et le Radium, *2*, 156; 1921.

[7] G. R. Harrison, *Photographic Sensitometry with Fluorescent Oils*, J.O.S.A., *11*, 113; 1925.

roughs of our laboratory found that the carboxylic ester of dihydrocollidine was peculiarly satisfactory. This substance is insoluble in water but can be dissolved in certain organic solvents, and if a plate is bathed in a solution of the material and allowed to dry, the surface of the plate is covered with a micro-crystalline deposit which fluoresces strongly under ultraviolet light and gives very good photographic images throughout the whole of the ultraviolet region so far investigated, which includes not only the region transmitted by quartz but the Schumann region, and even the shorter wave lengths available only in the vacuum spectrograph. For the very shortest wave lengths, plates prepared with this material have sensitiveness about equal to those made by the Schumann method, while in the near ultraviolet their sensitiveness is very much greater. (Compare Fig. 10.) The plates are far more convenient in use than Schumann plates. The fluorescent material can either be removed by washing the plate over with acetone before development or more conveniently by brushing the plate with a soft camel's hair brush as soon as it is in the developer, when the crystals become detached from the surface of the gelatine and can be brushed off. Up to the present time we have not been able to supply plates ready prepared with this material owing to certain practical manufacturing difficulties, but these are now being overcome and we expect very shortly to supply ultraviolet sensitive plates commercially. The solution is available.

SECTION II

Violet and Blue-Sensitive Materials. For wave lengths in excess of λ300 mμ, that is, for the whole spectral region transmitted by the atmosphere and available for astronomy, no special preparation of photographic materials is necessary. For spectroscopic purposes the plates which will give the maximum sensitiveness in this region are of the type of the Eastman 40, the blue sensitiveness of panchromatic plates being somewhat depressed. In pracitcal spectroscopy, where sufficient light is available, however, it is generally convenient to use a panchromatic plate in order that the longer wave lengths may be recorded at the same time as the violet and ultraviolet.

For many years a plate widely used in American observatories was the Seed 27 plate. The modern plate which corresponds to this is the Eastman 36. This plate is of medium speed and corresponding graininess. It has, however, now been supplanted largely by the Eastman 40 plate, a plate of somewhat higher speed and with very little increase in graininess.

Two plates of higher speed are made by the Eastman Kodak Company—the Eastman Speedway, which corresponds approximately to the old Seed Graflex plate, and the recently introduced Hyper Press, which is a plate of the highest possible speed, lower γ_∞, and somewhat increased graininess. In addition to these high speed plates, the Eastman Kodak Company manufactures the Eastman 33 and the Eastman

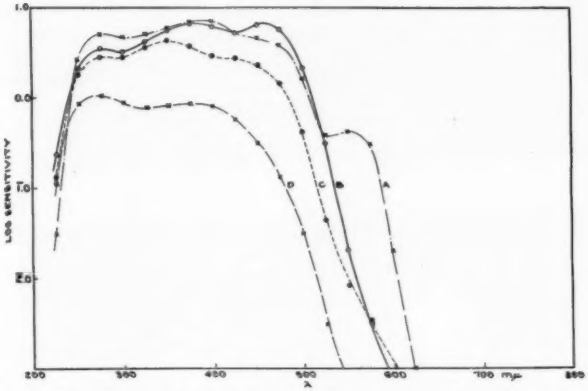

FIG. 11. *Spectral sensitivity curves of Eastman plates. A, Eastman Speedway; B, Eastman 40; C, Eastman 33; D, Eastman Process.*

Process plate, these having lower speeds and much higher degrees of contrast.

The spectral sensitivity curves measured in terms of the absolute energy required to give a density of 0.6 when developed to a γ of 0.8 of γ_∞ are shown in Figs. 11 and 12. It will be noticed that the Speedway plates have a secondary maximum of sensitiveness in the yellow-green, which must be taken into account, of course, in astronomical work. The general sensitometric properties of these plates are shown in the table on p. 758, their resolving power is shown in Table 4, and the graininess in Fig. 8.

For the photography of the corona during solar eclipses, it has been the custom of experts for many years to use double coated plates, made by superimposing an emulsion of the highest speed on the top of one of medium speed.

The glass on which plates are coated is often of considerable importance in scientific work. Photographic glass is selected from the glass made for use in windows, about 25 percent of the best window glass being considered suitable for photographic use. Until about ten years

ago such glass was made by blowing a large cylinder; the ends were cut off and it was opened down its axis, the glass then being allowed to flatten out under heat. Such glass always had a definite concave side, and the concave face was coated with the photographic emulsion, which gave a plate having a thicker coating in the middle and thin edges. Modern glass, however, is made on machines which produce glass showing no definite concavity, the surface being somewhat wavy and some-

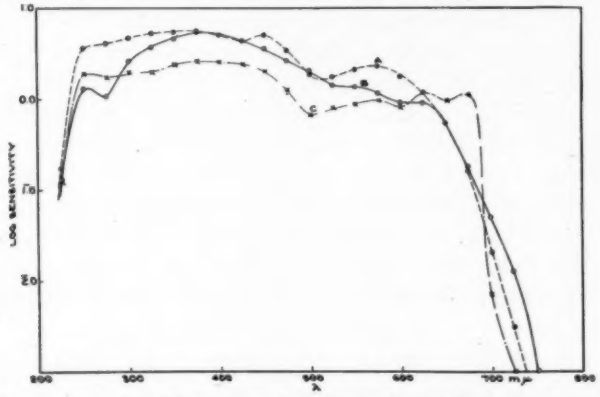

FIG. 12. *Spectral sensitivity curves of Wratten plates. A, Wratten Panchromatic; B, Wratten M; C, Wratten Hypersensitive Panchromatic.*

times having two or three waves in an 8×10 plate. On the whole, this glass gives plates superior in uniformity to those coated on the older glass. Where even thickness of the coating is of paramount importance, it is necessary to use plate glass as the support. This unfortunately is very expensive.

In many spectrographs it is necessary to bend the plates, and it is customary therefore to coat such plates on glass which averages not more than 1 mm in thickness, plates of this thickness being available in lengths up to 18 inches. Recently a demand has arisen for even thinner plates owing to the use of grating spectrographs of short focal length, and ultra-thin glass is now available of an average thickness of 0.7 mm, this glass, however, being somewhat inferior in flatness and giving a good deal of trouble from breakage. This ultra-thin glass cannot be supplied in sizes larger than 8×10 inches.

SECTION III

Panchromatic and Other Color Sensitive Materials. The panchromatic plates supplied by the Eastman Kodak Company are made in a special

department of the research laboratory. As a result of this, while only three types of plates are manufactured commercially, special materials of many varieties can be obtained on request, and scientific workers are invited to send to the research laboratory a description of the work they are doing for suggestions as to materials which might be especially suitable for their use.

FIG. 13. *Wedge spectrograms of Type B and Type C panchromatic plates.*

The panchromatic materials available result from a combination of methods of optical sensitizing with certain basic emulsions, and since any method of optical sensitizing can be combined with basic emulsions, the subject can most easily be understood by treating the two components separately.

Three basic emulsions are used in our laboratory:

1. A very high speed emulsion giving the utmost sensitiveness with a reasonable amount of graininess.

2. An emulsion similar to the Eastman 36 (or Seed 27), but which, owing to the methods of optical sensitizing, shows much higher total sensitiveness.

3. An emulsion of great contrast and of moderate speed and graininess.

In addition to these three materials, other special emulsions, such as process emulsion, lantern slide emulsion, or an extremely contrasty slow bromide emulsion, valuable particularly in solar photography, can be sensitized if occasion calls for it.

Two chief types of optical sensitizing are employed. These are best illustrated by the wedge spectra, which are madeby tungsten light on a

grating spectrograph and are shown in Fig. 13. Sensitizing Type B[8] is that which gives a sensitiveness curve throughout the spectrum most closely resembling the sensitiveness of the eye except for the excess of sensitiveness in the blue.[9] Type C gives sensitiveness concentrated

FIG. 14. *Wedge spectrogram of Wratten Hypersensitive Panchromatic plate.*

towards the red end of the spectrum and has the property, in addition, of giving the highest possible total sensitiveness to the material.

Before dealing with other possible types of sensitizing it may be well to identify in terms of this discussion the materials which are regularly

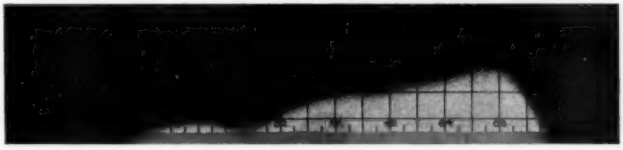

FIG. 15. *Wedge spectrogram showing type F sensitizing.*

manufactured by the Kodak Research Laboratory. The Wratten Hypersensitive Panchromatic plate is that which would here be designated as 1-C; that is, it is the high speed emulsion Type 1 sensitized with the C type of sensitizing, its spectrum being shown in Fig. 14. The Wratten Panchromatic plate, which is used for all general commercial photography and color photography, is an emulsion of Type 2 sensitized with sensitizing Type B. (See Fig. 13.) The Wratten M plate is emulsion Type 3 and sensitizing Type B. It could be designated therefore as plate 3-B and is the most generally useful plate for precision spectrography throughout the spectrum except for the red. Several observatories use the same emulsion sensitized with sensitizing Type C for the photography of the spectrum in the red—3-C.

[8] So named because of an earlier Type A which is now obsolete and needs no description.

[9] The commercially available materials sensitized with the B type of sensitizing are known to us by the name of "orthopanchromatic" materials; those with the C type, as "hyperpanchromatic" materials.

In addition to these sensitizings other plates specially sensitized can be made to order. Thus, although the *C* type of sensitizing gives the maximum sensitizing which can be obtained for the H-alpha line, the fact that the sensitiveness falls off very rapidly towards the red side of the H-alpha line gives trouble in some spectroscopic work, and it is more advantageous to use a sensitizing of Type *F* shown in Fig. 15, since, although the maximum of sensitiveness is slightly lower, the extension through the red is more uniform.

FIG. 16. *Wedge spectrogram showing type D sensitizing.*

Another special sensitizing, Type *D*, shown in Fig. 16, has a somewhat higher maximum at the *D* lines than Type *B*, and for work where maximum sensitiveness in the yellow is required, the use of this special method will enable shorter exposures to be attained.

It may be desirable at this point to make some suggestions as to the best plate for use in certain types of astronomical work. For general stellar photography where the shortest possible exposures are required, Professor Shapley has found the plates of Type 1-*C* to be particularly advantageous. They have very high general sensitivity and their special sensitivity in the red permits shorter exposures than can be attained with other plates. They are, of course, not so sensitive for *A* and *B* type stars as the best blue-sensitive materials, but on the other hand are very much more sensitive for the *M* type of stars. These plates are also valuable for the determination of color indices using widely separated wave lengths, the magnitude in the red using a red filter over the plate being compared with images obtained on blue-sensitive plates.

Another possible application for plates of this type is for the direct photography of stars in moonlight or in the vicinity of city lights. The exposure of a blue-sensitive plate is limited[10] even on a dark night far from any city by the diffuse light from the sky. After a number of hours the plate begins to fog, but in moonlight or near city lights this occurs much more quickly. The scattered moonlight responsible for the fogging is principally blue light. When a red filter and red-sensitive

[10] Extract from Dunham, *loc. cit.*

panchromatic plates are used, exposures of 5 hours are possible with the full moon in the sky, and no more fog results in those five hours than in 5 minutes on blue-sensitive plates without a filter. The advantage of using this combination when photographs must be taken in the vicinity

FIG. 17. *Wedge spectrogram of isochromatic plate.*

of lights of a large city would, of course, be less because city lights are redder than moonlight.

Very important instruments in astronomical observatories are the visual refractors which are generally used by photographing in the

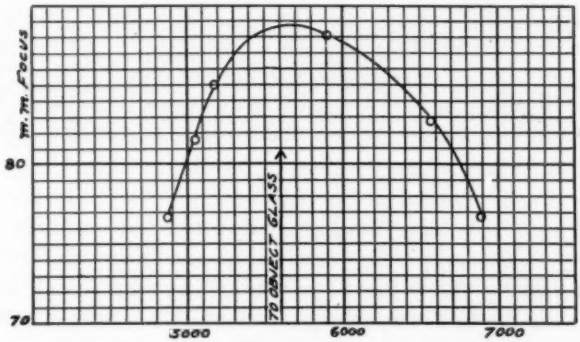

FIG. 18. *Focal curve of the objective of the Lick Observatory refractor.*

visual maximum through a yellow filter. For this purpose it has been customary to use so-called "Iso" or "Ortho" plates sensitized to give a maximum in the yellow-green, as shown in Fig. 17. The best plate from the point of view of focus depends, of course, upon the focal curve of the objective. My thanks are due to Dr. Aitkin for Fig. 18 showing the curve of the Lick 36-inch refractor, from which it will be seen that a panchromatic plate of the general type of sensitizing of the Wratten Panchromatic type, 2-*B*, would be at least as satisfactory as the older "ortho" materials, while the general sensitivity of these plates for wave lengths transmitted by the filter is much higher than that of the older

materials. For use with refractors, therefore, our recommendations are to use a yellow filter (the Wratten filter No. 12 has been adopted by most of the important observatories) together with a plate sensitized with the *B* type of sensitizing.

For most work where greater contrast is not a disadvantage, the lower graininess of the Wratten *M* plate will be an advantage, while where maximum sensitivity is required and low contrast is not a disadvantage, emulsion Type 1 with *B* type sensitizing can be supplied.

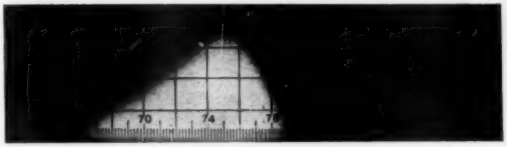

FIG. 19. *Wedge spectrogram of kryptocyanine plate.*

SECTION IV

Extreme and Infrared-Sensitive Materials. With the introduction of kryptocyanine, discovered by Adams and Haller in 1919, it became possible to make photographic records beyond the limits of the visible spectrum. The sensitizing curve of kryptocyanine is shown in Fig. 19. This dye is used for sensitizing the Eastman extreme red sensitive plates, which can be used not only for the photography of spectra in the extreme red but also for other special types of photography. Thus, they could certainly be used for the determination of color indices with a view to distinguishing small differences in the classes of red stars. Some work is already in progress in this field.

Dr. W. H. Wright applied plates sensitized with kryptocyanine to the photography of terrestrial objects in the presence of haze and photographed the Yosemite Valley from the Lick Observatory. Captain A. W. Stevens has employed an extreme red sensitive film in his well known long distance photographs from airplanes, the most notable of which, photographing the Andes range at a distance of 310 miles, shows the haze over the Pampas silhouetted against the mountains in such a way as to demonstrate very clearly the curvature of the earth. Wright has applied kryptocyanine plates to the photography of Mars and other planets, his results suggesting that Mars is surrounded by an atmosphere through which the surface features of the planets can be photographed only with infrared light. An interesting application of the same principle has recently been made by Professor Trumpler of the Lick

Observatory in photographing the Orion nebula.[11] A long exposure on an ordinary plate cannot show faint stars within the nebular region because the light of the nebula soon blackens the plate and masks their images, but the nebular light is almost entirely blue-green and visible red, and a photograph on an extreme red sensitive plate with a filter

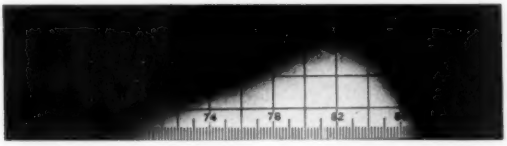

FIG. 20. *Wedge spectrogram of neocyanine plate.*

transmitting only infrared light showed many faint stars with very little nebulosity.

In 1925 a new dye was discovered by H. T. Clarke, to which the name "Neocyanine" was given, and since then plates have been prepared with this dye under the name of "Infrared Sensitive plates." These plates have the spectrum shown in Fig. 20.

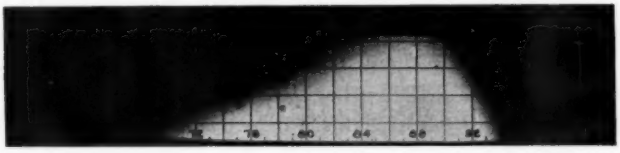

FIG. 21. *Wedge spectrogram of new series infrared sensitive plate.*

It will be noticed that the spectrum shown in Fig. 20 falls off to λ900 mμ, but beyond this point hypersensitized neocyanine plates show a weak extension towards the infrared, which has enabled Babcock to photograph the solar spectrum as far as λ1163 mμ.

Recent work in the Kodak Research Laboratories on sensitizing dyes has enabled us to improve the sensitiveness of the infrared sensitive plates very considerably, and the New Series infrared plates have the spectrum shown in Fig. 21 and have more than ten times the sensitiveness of neocyanine plates at λ900 mμ. These plates will, we believe, be of real assistance in the photography of the infrared portion of the spectrum.

[11] Dunham, *loc. cit.*

Special sensitizers of other types are available and new sensitizers are being found rather rapidly, so that if any special problem in the photography of the infrared arises, physicists are invited to write to our research laboratories for information as to the latest developments.

All panchromatic and infrared sensitive plates are increased in sensitivity by hypersensitizing with ammonia, the best procedure being to bathe the plate for one minute in a 4 percent solution of ammonia at a temperature not above 55°F and to dry the plate as rapidly as possible in the blast of air from a fan.This approximately doubles the red sensitivity of plates of the *B* and *C* type of sensitizing and increases many times the sensitiveness of the extreme red sensitive and especially of the infrared sensitive plates. For infrared sensitive plates hypersensitizing is almost essential. We have recently found that extremely good results in hypersensitizing can be obtained by the use of triethanolamine in place of ammonia, a half percent solution of this material in distilled water giving results at least as good as those with ammonia with less danger of fog and spots.

THE MEASUREMENT OF REFLECTION-FACTORS IN THE ULTRAVIOLET

By A. H. Taylor
[Lighting Research Laboratory General Electric Company, Nela Park, Cleveland, Ohio. Received September 10, 1931]

Reflection-factors in the ultraviolet have been measured by a number of investigators. Hulburt,[1] using a grating spectrometer, photoelectric cell and quadrant electrometer, measured the specular reflection of a number of metals for various wave lengths in the ultraviolet. Stutz,[2] using a quartz prism spectrograph, measured the spectral reflection of many pigments. In his measurements the light was incident normally to the surface of the material and the light reflected at an angle of 50 degrees from the normal entered the spectrograph. The spectral reflection values were obtained photographically. Coblentz[3] and his colleagues have obtained reflection-factors for polished metals by use of a quartz spectrometer and a thermopile. Luckiesh,[4] using a quartz spectrograph, obtained spectral reflection-factors for a number of materials by a photographic method. Stutz[5] used two small integrating spheres in combination with a quartz spectrograph to determine the ultraviolet transmission and reflection-factors of thin paint films. A photographic method was used to evaluate the reflected radiation. Apparently magnesium carbonate or oxide was used as the standard of reflection, although this is not specifically stated.

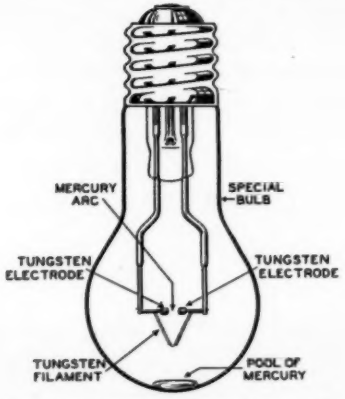

Fig. 1. *Mazda Sunlight Lamp (Type S-1).*

* Wave lengths in Angström units.

Since many of the materials in which we are interested diffuse the reflected radiation to some extent, it is desirable to use some method of measurement in which the reflected radiation is integrated. Also, it should be an *absolute* method, i.e., it should not require a standard of known reflection characteristics.

The author has recently designed and had built an *absolute* type of integrating reflectometer for use in measuring spectral reflection-factors in the ultraviolet. The principles of operation are similar to those em-

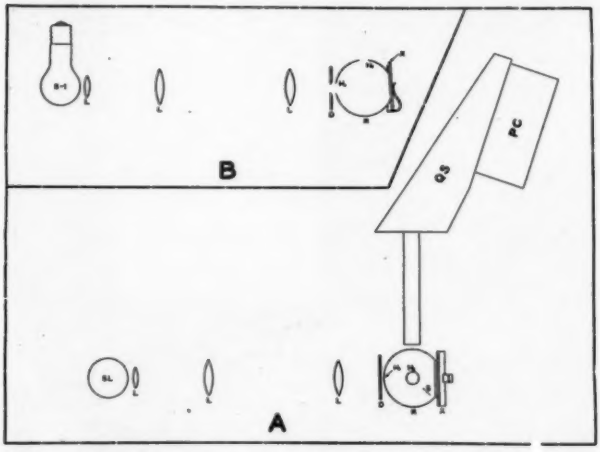

FIG. 2. *Plan and elevation diagrams of ultraviolet reflectometer.* (*S-1*) *Mazda Sunlight lamp in quartz bulb;* (*L.L.*) *quartz lenses;* (*D*) *diaphragm slightly smaller than holes* (H_1, H_2); (*R*) *four-inch hollow sphere;* (*X*) *test specimen;* (*QS*) *quartz spectrograph;* (*PC*) *photocell cabinet.*

ployed in a sphere reflectometer previously designed by the author[6] for measurement of diffuse reflection-factors for light. Fig. 2A shows a plan view of the light-source, quartz lenses, reflectometer sphere, quartz monochrometer and photoelectric cell cabinet. Fig. 2B shows an elevation of the lamp, lenses and sphere, and Fig. 3 is a photograph of the apparatus. The light-source is a Sunlight Mazda lamp (Fig. 1) in a quartz bulb. Since the arc length is only about 5 mm, this furnishes a very concentrated source of ultraviolet radiation. The reflectometer sphere is smoked inside with magnesium oxide. It is 4 inches in diameter, and has two holes H_1, H_2, each 3/4 inch in diameter. When the sphere is in the position shown in Fig. 2B the focused image of the arc passes through hole H_1 and falls upon the test specimen, X, which is placed against a hole in the opposite wall of the sphere. The normal to the plane of the

test surface makes an angle of approximately 5 degrees with the incident light, so that light specularly reflected will not pass out through hole H_1.

The quartz monochromator, QS, is a Hilger quartz spectrograph to which has been added a photoelectric cell cabinet, PC. In front of the cell is a slit adjustable in width and position and a totally reflecting

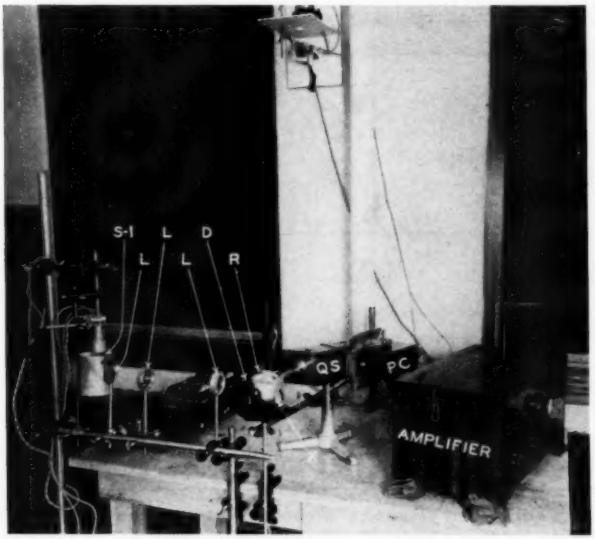

FIG. 3. *Photograph of ultraviolet reflectometer shown diagrammatically in Fig. 2.*

quartz prism to reflect the radiation into a quartz sodium photoelectric cell. The monochromator collimator slit is placed near a small hole in the sphere wall through which a small spot on the opposite wall is viewed. This spot is screened from the test surface X by means of a small opaque screen S. The reflectometer sphere R can be rotated 90 degrees about an axis coinciding with the axis of the collimator telescope. In this position the light enters the sphere through hole H_2 and falls upon the sphere wall at a point unscreened from the spot observed by the monochromator. Fig. 3 is a photograph of the apparatus.

Since the energy received by the photoelectric cell is quite small it is necessary to amplify it. For this purpose a two-stage direct-current amplifier is used. The image of a lamp filament reflected from the galvanometer mirror is focused on a scale 15 feet long, placed at the opposite

side of the room. For most wave lengths from λ2482 to λ4047 it is possible to obtain practically full scale deflections.

THEORY OF REFLECTOMETER

The theory of this reflectometer is based upon the principles employed in the photometric integrating sphere,[7] and is identical with that of the Taylor reflectometer[6] which measures diffuse reflection-factors for light. The same principles apply when the measurement is for a single wave length as when the integrated light is measured.

The fundamental theory of the integrating sphere[7] assumes the use of an interior coating which is a perfect diffuser, i.e., one which reflects the light or radiation in accordance with the cosine law of emission. Such a surface, when illuminated, would appear equally bright at all angles of view. If the inner surface of a hollow sphere is a perfect diffuser, it can be shown mathematically that each element of the surface illuminates all other elements of the surface uniformly, regardless of their position relative to it.

Let F = total flux of wave length λ entering the reflectometer.
R_s = diffuse reflection-factor of sphere surface for wave length λ.
R_x = diffuse reflection-factor of test surface for wave length λ.
B = brightness of spot observed when light is incident directly on sphere wall.
b = brightness of spot observed when light is incident on the test surface.
K = a constant.

When the radiation entering the sphere through hole H_1 falls upon the test surface, none of the directly reflected flux can reach the point observed by the monochromator because of the screen S. Hence it must be reflected by the test surface once and the sphere surface once before any of it reaches the spot observed. Thus the flux which is effective in illuminating the spot observed is R_xR_sF, and the brightness of the spot is proportional to this product; hence $b = KR_xR_sF$, where K is a constant of the apparatus.

When the sphere is turned so that the flux entering it passes through hole H_2 and falls on the sphere wall at a point *unscreened* from the spot observed, the flux effective in illuminating the latter is R_sF, and the brightness of the spot is

$$B = KR_sF.$$

Therefore

$$\frac{b}{B} = \frac{KR_xR_sF}{KR_sF} = R_x.$$

Thus the brightness ratio b/B, when the sphere is in the two positions, gives directly the diffuse reflection-factor of the test surface at the wave length for which the photoelectric cell cabinet is adjusted.

SOURCES OF ERROR

As stated above, the fundamental theory of the integrating sphere and of this instrument assumes that the surface is perfectly diffusing. This requirement is never completely fulfilled. The author has previously analyzed the action of a sphere at the Bureau of Standards[7] where the diffusion characteristics of the sphere wall and the translucent window had been measured. It was found that if a concentrated beam of light was to be compared with a uniformly distributed flux such as that from a point source at the center of the sphere, the most favorable position for incidence of the concentrated beam was approximately 90 degrees from the sphere window. In the reflectometer described above the light is incident upon a spot 90 degrees from the spot observed by the monochromator. While this reflectometer does not employ a diffusely transmitting window such as is used in the integrating sphere, it would seem that there exists a close analogy between the actions of the two instruments and that the experimental conditions used in this reflectometer are approximately the best that can be used to minimize the effect of imperfect diffusion.

Some light (or radiation) is lost through the holes H_1, H_2 and the small hole through which the monochromator views the sphere wall. The area of these three holes in the instrument described is approximately 2 percent of the total sphere area. The effect of these holes and the absorption of radiation by the test surface which replaces part of the sphere surface may be analyzed as follows:

When light (or radiation) flux F enters the reflectometer sphere R through hole H_1 and falls upon the test surface X, the amount reflected to the sphere walls is R_xF. If the test surface is a perfect diffuser, the amount lost through the holes is approximately $0.02R_xF$. With the exception of a very small amount which strikes one side of the opaque screen S the remainder, $0.98R_xF$, is incident upon the sphere walls at points unscreened from the spot observed, and the brightness of the spot observed is directly proportional to this amount. When light enters the sphere R through hole H_2 and falls on the sphere wall at a point unscreened from the spot observed, the brightness of the spot observed is directly proportional to the intensity of the flux F. Thus it is seen that if the test surface is a perfect diffuser, the maximum error to be expected

because of light lost through the holes is 2 percent. If the reflection from the test surface is perfectly specular, so that none of the first reflected flux is lost through the holes, no error of measurement results from the presence of the holes. Since very few surfaces are even approximately perfect diffusers, the error just discussed probably does not usually exceed 1 to 1 1/2 percent.

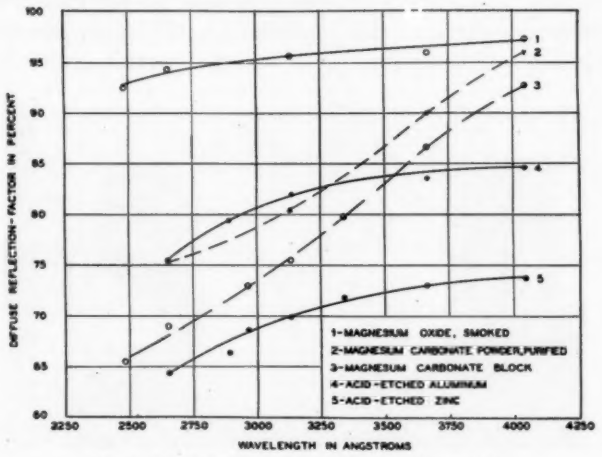

FIG. 4. *Spectral reflection curves for several materials.*

In Fig. 4 are shown spectral reflection curves for magnesium oxide and carbonate, acid-etched aluminum and zinc, as obtained with the apparatus described above. It is seen that magnesium oxide has a reflection-factor of 95 percent or more for wave lengths longer than λ2900. Magnesium carbonate is not nearly as good a reflector for the ultraviolet, although its reflection-factor for light is above 95 percent. In order to determine whether the magnesium carbonate block tested was typical, a specimen was made up by compressing purified magnesium carbonate powder. This gave reflection-factors higher than those obtained for the block of magnesium carbonate, though still much lower than the magnesium oxide. The acid-etched aluminum was measured during an investigation of methods of etching aluminum to obtain high reflection-factors for light and for ultraviolet.[8]

MEASUREMENT OF RELATIVE REFLECTION-FACTORS

At the present time there is much interest in the reflection-factors of materials for use in the field of dual-purpose lighting,[9] where the lighting

units furnish good illumination and at the same time some ultraviolet radiation for health maintenance. It has been definitely proved that radiation in the spectral region λ2800 to λ3200 is especially effective in the prevention and cure of rickets and in general maintenance of health. The wave length of the mercury spectrum most effective, per unit of energy, in the production of erythema (reddening of the skin) is λ2967.

The author has recently devised apparatus for the measurement of *relative* reflection-factors in this important spectral region. The apparatus does not include a monochromator, but the spectral sensitivity of the

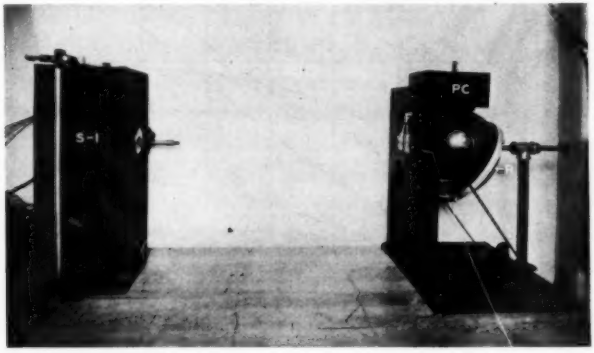

FIG. 5. *Apparatus for the measurement of* relative *reflection-factors in the ultraviolet. (S-1) cabinet containing MAZDA Sunlight lamp (Type S-1) and quartz lens; (S) eleven-inch hollow sphere; (PC) cabinet containing blue-fluorescing glass, ultraviolet filter and photocell; (F) quartz and Pyrex filters.*

device is such that it appraises the reflected radiation approximately in accordance with its erythemal effectiveness.[10,11] Fig. 5 shows a photograph of this apparatus. *S*-1 is a housing which encloses a Mazda Sunlight lamp (Type S-1) and a quartz lens. *S* is an eleven inch hollow sphere coated on the inside with magnesium oxide. The focused radiation from the mercury arc of the *S*-1 lamp passes through one of the filters *F* (quartz or Pyrex), through a small hole in the sphere wall and is received by the test surface (reflector *R*) placed over a hole in the opposite wall. At the top of the sphere the cabinet *PC* is placed over another hole, which is screened from the test surface. This cabinet contains a filter of Corning red-purple Corex glass to filter out the visible radiation and transmit only the ultraviolet, a piece of blue-fluorescing glass and a potassium photoelectric cell to measure the fluorescent brightness of this glass.

When exposures are made first through 1 mm Pyrex and then through quartz, the spectral sensitivity of the measurement is as shown in Curve *F*, Fig. 6. The spectral erythemal effectiveness of radiation is approxi-

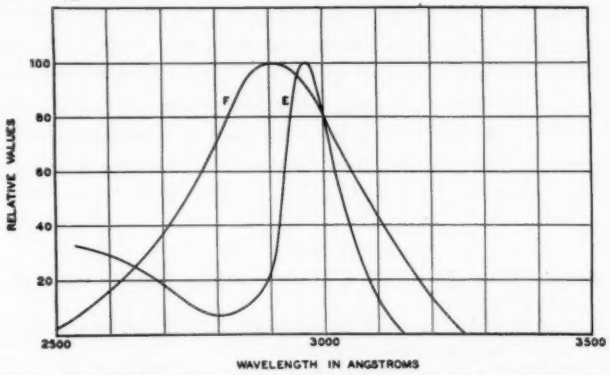

FIG. 6. *(E) Spectral erythemal effectiveness of ultraviolet radiation; (F) spectral sensitivity of blue-fluorescing glass under conditions of use.*

mately as shown by Curve *E*. Computations combining the spectral sensitivity of the fluorescent device and the energy distribution of an *S*-1 lamp show that the spectral centroid of the energy measured is ap-

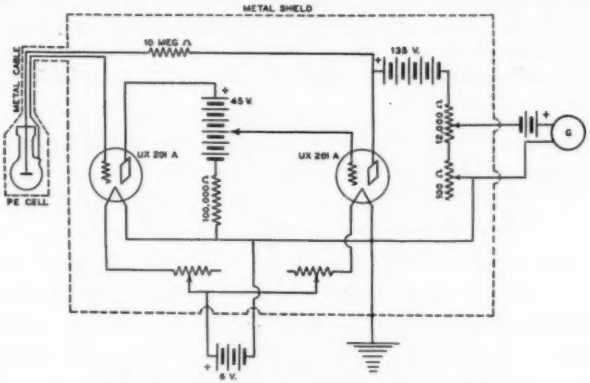

FIG. 7. *Simplified diagram of direct-current amplifier.*

proximately λ3050. If a standard of known reflection-factor at this wave length is used, the reflection-factors of flat specimens or reflectors such as are used in sunlamps can be measured. The values so obtained are of great value in determining the ultraviolet reflecting efficiencies of reflectors and materials for use in the dual-purpose lighting field.

DIRECT-CURRENT AMPLIFIERS

A simplified diagram of the direct-current amplifier used with both of these devices is shown in Fig. 7. The direct proportionality of response to the incident energy was tested by use of a set of sectored disks, using a direct-current lamp as the source of radiation. Under the conditions used there was a direct proportionality of response under a wide variety of conditions. It is not the purpose of this paper to discuss amplifiers, however, hence those interested are advised to consult some of the recent papers on the subject. Both instruments require a sensitive amplifier, since the energy to be measured is very small.

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LAMINARY REFLECTION GRATINGS FOR INFRARED INVESTIGATION

By C. Hawley Cartwright
[California Institute of Technology, Pasadena, Calif.]
Received August 26 1931]

It is the purpose here to give the intensity distribution of laminary reflection gratings[1] for use in the infrared spectrum and several methods for making them. The best choice among the various methods to be described can be determined by the apparatus available and the experience one has had with the different types of technique required. The advantages of this kind of grating suggests that its use should be more general. A new method for making an echlette grating is also described.

The laminary reflection grating has the advantage over a transmission wire grating or a reflection grating composed of equally spaced reflecting and absorbing strips that it can give four times more intensity and twice the resolving power. The laminary grating has also some advantages over the echlette grating: (1) it can be more easily constructed; (2) although for a particular wave length, the echlette grating can give $(\pi/2)^2$ more intensity than a laminary grating; the high intensity of the second, third, fourth, etc. order spectra may make it less desirable than the laminary grating which has no even order spectra and for which the intensities of the higher orders rapidly diminish. Absolute wave-length determinations can be made accurately with the laminary grating for the spectrum is symmetrically located on both sides of the normal which gives a strong zero order spectrum.

Fig. 1 shows the intensity distribution of a laminary reflection rgating when the angle of incidence is equal to the angle of the reflected radiation as shown in the drawing, a condition approximately fulfilled in most spectrometers. The first order of any wave length, λ, occurs for the grating turned through an angle $\theta = \sin^{-1}\lambda/4d$ to the normal. The intensity distribution is calculated by considering the amplitude from the top laminations and vectorially adding to it the amplitude from the bottom surfaces. The intensity of the first order spectrum is given by the equation:

$$I_1 = 2A^2 + 2A^2 \cos \pi\left(1 + \frac{\lambda_0}{\lambda}\right). \qquad (1)$$

[1] R. M. Badger and C. H. Cartwright, Phys. Rev. *33*, 692; 1929. Dr. Badger, I believe, was the first to see the possibility of using a laminary grating by reflection for work in the extreme infrared spectrum.

The wave length, λ_0, is four times the height of the laminations.

The intensities of all of the even orders are zero.

$$I_2 = I_4 = I_6 = 0. \tag{2}$$

In Fig. 1 is also plotted the intensity distribution of the third order spectrum which accompanies any desired wave length, λ, as given by the equation

$$I_3 = 2B^2 + 2B^2 \cos 3\pi\left(1 + \frac{\lambda_0}{\lambda}\right), \text{ where } B = \frac{A}{3}. \tag{3}$$

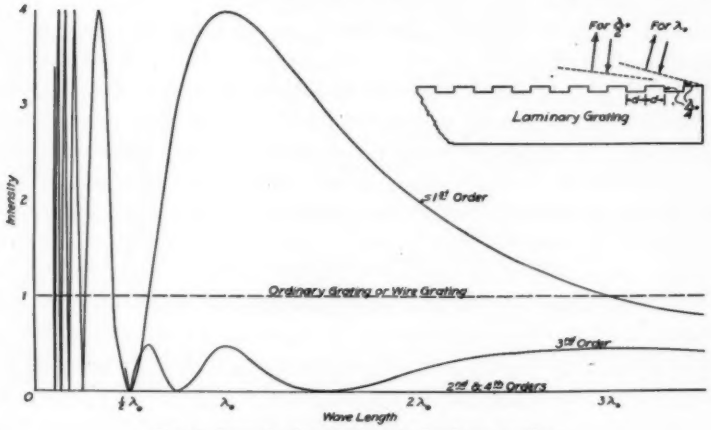

FIG. 1. *Intensity distribution of a laminary grating.*

Thus for $\lambda = 3/2\lambda_0$, there will be no interference from any higher orders.

The broken line in Fig. 1 shows the relative intensity obtained from a grating of equally spaced absorbing and reflecting strips or from a transmission wire grating as often used for infrared work.

For a laminary grating, the lines must be spaced linearly along the grating with sufficient accuracy to give the necessary resolving power and also the height of the laminations must be sufficiently equal to obtain the correct interference from the bottom and top surfaces. Since the ordinary ruling or linear dividing engine is constructed to give only accurate spacing of the lines, several methods will be given to obtain the required accuracy for the height of the laminations in order to have the grating work efficiently.

The width of the laminations is determined by the resolving power desired and the height is determined by the wave length that is to be investigated.

The intensity curve in Fig. 1 shows that the laminary grating is only useful for a short range of wave lengths below λ_0 and is particularly valuable for $\lambda = 3/2\lambda_0$ where there is no interference from any of the higher order spectra. It may happen, also, that the third order spectrum is stopped by the windows; such is the case when crystalline quartz is used for the windows when investigating the infrared region of 50 μ to nearly 150 μ.

A method of isolating the infrared from the more intense shorter wave lengths is to make the mirrors and the windows relatively rough for the shorter wave lengths to diffuse the light in the central image; whether it is best to have the grating rough can only be determined by careful analysis of the particular problem for which the grating is to be used. If the

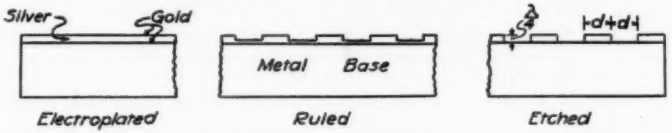

FIG. 2. *Laminary grating by electroplating.*

intensity distribution is known approximately for the light falling on the grating, the disturbance of the short wave lengths can be estimated. If the surfaces of the grating are flat, the intensity from an odd n^{th} order spectrum is reduced to about $1/2n^2$ of the intensity falling on the grating. If the surfaces of the grating are sufficiently rough to completely scatter a short wave length, the fraction of that energy to go through the exit slit is $A/4\pi 1^2$ where A is the area of the exit slit and 1 is the focal length of parabolic mirror used for illuminating the grating. The effectiveness of this diffused disturbance is further greatly reduced if a completely compensating type of thermocouple is used.

METHODS OF MAKING LAMINARY GRATING

I

Fig. 2 shows schematically one method used for constructing a laminary grating that is particularly adapted for extreme infrared work. A heavy metal base (we used a piece of speculum metal $4'' \times 4'' \times 3/4''$) is ground and polished until it is flat. It is electroplated with gold for protection from acid, then with silver to give most of the height necessary for the laminations, and finally with gold to protect the silver from acid. The correct position of the silver anode to give a uniform coat is determined by depositing a partially transparent surface of silver on to the gold. The silver can be removed with nitric acid until the best ar-

rangement is found. It is important to deposit the metals slowly and to keep the solution in agitation in order to get a uniform and smooth surface. The final gold surface can be polished flat if desired. The grating is then ruled by making many fine lines with a ruling machine and then skipping a space or by using a weighted tool on a linear dividing engine, good milling machine, or good lathe. The depth of the rulings need not be very accurate for the silver is etched by dilute nitric acid to the lower gold surface as shown in Fig. 2. The etching should be started by using about 1% nitric acid bath for 15 minutes and then gradually increasing the strength of the bath to 7% until the bottom gold is exposed. The grooves are etched almost vertically for the gas evolved while etching protects the side walls from undercutting.

A very satisfactory silver plating solution is the following: Dissolve 3 oz. silver nitrate in 32 oz. of distilled water and add slowly a strong solution of potassium cyanide until no more white precipitate is formed. The precipitate should be washed six times by filling the bottle with distilled water, shaking, allowing the precipitate to settle, and pouring off the water. A solution of potassium cyanide is added slowly until the precipitate is disolved and then an excess of potassium cyanide is added—about as much as was used in dissolving the precipitate. Water is added to make one gallon of solution.

The gold plating solution consisted of 8 oz. of potassium cyanide dissolved in a gallon of water. Some object of no value is first gold plated in this solution to properly charge the solution with gold.

II

A method that is easier than the one above if an evaporating apparatus is available is to deposite cadmium by evaporation on to a flat plate of glass.[2] There is much time and work saved by the evaporation process for commercial thick plate glass can be selected which is sufficiently flat for most gratings. The evaporated surface can be made of uniform thickness by depositing the metal at a sufficiently great distance from the heater. An evaporated surface of cadmium is slightly rough but can be easily polished if desired. The advantage of cadmium over other metals is that it can be deposited in a heavy layer without any tendency to peel from the glass and cadmium can be ruled nicely with a sharp tool.

After a coat of cadmium of the desired thickness is deposited, the grating is ruled with weighted steel tool. The pressure on the tool is

[2] C. H. Cartwright and J. Strong, R.S.I. *2*, 189; 1931.

sufficient to completely cut through the cadmium but not to scratch the glass. The entire grating is then covered with a thin surface of evaporated gold or chromium.

A cadmium layer 30 μ thick was ruled and the remaining metal held tenaciously to the glass.

III

The wax used for Epiphone or Dictaphone records is ideal to cut with a tool. The metal or glass base was first coated with a thin layer of rosin and beeswax (half of each) and then the wax from an Epiphone record

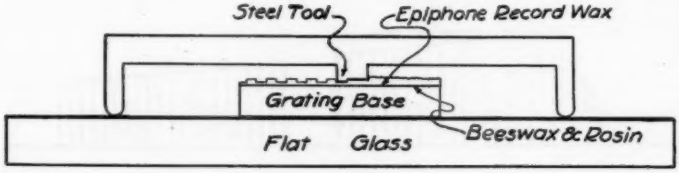

FIG. 3. *Wax grating.*

was heated and cast in a layer about 2 mm thick. A grating with grooves of any desired shape can be ruled by a tool as shown schematically in Fig. 3.

The plate glass to control the vertical height is selected for the accuracy desired. The grating is made reflecting by evaporating a metal such as gold onto it. The metal must be evaporated slowly and at a great distance so that the wax will not melt. Ordinary chemical silvering did not adhere to the wax at all. The wax did not flow and lose its flatness and shape in time.

IV

Several photographic methods were used for forming a laminary relief but chrom-gelatine[1] was satisfactory and could be most easily prepared. Ten g of a soft gelatine is soaked for 30 minutes in 60 cc of water and then heated in a water bath to about 50° C (it is important not to heat the gelatine above 54° C). Five cc of pure alcohol and 5 cc of a saturated solution of potassium dicromate in water is added. The solution should be filtered three times through cotton and an amount, determined by trial, is made to flow from a warmed pipette onto a warm piece of selected plate glass. The glass plate should be carefully leveled and kept in a well ventilated dark room to dry. The grating is produced by exposing the sensitized gelatine to the parallel rays from the

sun through a master grating made of equally ruled opaque and transparent lines of chemically deposited silver or of evaporated cadmium on glass. The time necessary for the contact print is about 20 seconds. The exposure must be long enough so that the gelatine will adhere firmly to the glass yet not too long so that the relief will not be perfectly developed. The relief is developed by completely washing away the unexposed gelatine in warm water. If methyl blue dye is dissolved in the water, it is easier to tell when the grating is fully developed. The gelatine can be rubbed with the finger or wet cotton to facilitate the

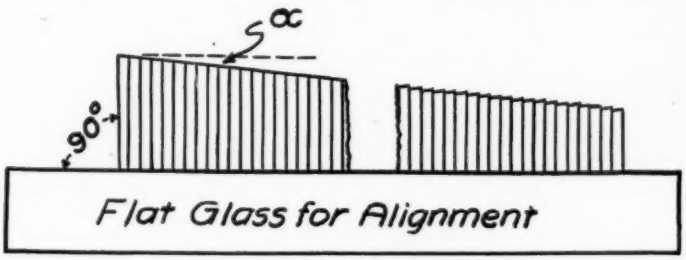

FIG. 4. *Echlette grating.*

developing. The grating is dried for about 5 minutes and made reflecting by an evaporated coat of gold or chromium.

The chrom-gelatine can be kept in a dark room and reheated to 50°C and used for several days.

V

If there is at one's disposal a good antistigmatic lens, a possible method of making laminary gratings is by photographing a picture of equally spaced black and white strips on a chrom-gelatine plate prepared as previously described. Since a long exposure can be made, a slow lens and a filtered light can be used very well. By this method, any desired grating space can be obtained. One plate of a Levy half-tone plate can be photographed by transmitted light. The accuracy of the rulings of a Levy half-tone plate is about as good as it is possible to obtain.

A METHOD OF MAKING ECHLETTE GRATINGS

If there is at one's disposal some thin plate glass, the following method can be used for making echlette gratings. The glass plates are cut and polished on both edges as shown in Fig. 4 and then each plate is rotated through 180 degrees as shown in the right of Fig. 4. The angle is calcu-

lated to give the grating the desired characteristics. The plates are assembled in a frame which presses the back polished edge against a heavy plate of flat glass by a pressure on a piece of soft rubber which rests on the front echlette surface. The plates are moved individually back and forth over the glass flat until they are all in contact with the base as tested by the interference of a sodium light. By applying the vertical force on the plates through the rubber while the plates are back and forth horizontally, it is possible to cheat the friction which ordinarily prevents the plates from being perfectly aligned.

I am thankful for the help and suggestions of Mr. Julius Pearson.

ON THE SPECTRA OF GASES APPEARING IN THE EARLY STAGES OF THE SPARK

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RECEIVED JULY 27, 1931]

INTRODUCTION

The adaptation by Beams,[1] Lawrence,[2] and others[3] of the Kerr cell electro-optical shutter of Abraham and Lemoine in a considerably improved form to the measurement of the time intervals between appearances of lines in the spectra of spark discharges for various elements has perhaps opened the way to the methods for the investigation of the physical process in the early stages of spark discharge, because the cell makes it possible to observe the sparks only during any desired short intervals of time from the instant of break down of the potential between the electrodes. The results hitherto obtained have made it clear that sparks break down in time intervals of about 10^{-8} sec after the application of electric fields and that during such a short interval of time, the potential difference across a spark gap falls down from its initial high value to the low one characteristic of arcs. The recent works of Lawrence and Dunnington[4] and of Hámos[5] point out that only air lines are observable in the early stages of spark discharge and then the spark lines of electrodes begin to appear at the later time of 50×10^{-8} sec after the collapse of the potential and the metal lines as well as the air lines are, in the duration of this stage, remarkably broadened; for example, the total width for doublet lines $3d_{1,2}-4f_{1,2}$ of zinc extend over about 45A and the corresponding lines of cadmium and magnesium over about 30A. There is little doubt that such a large broadening of lines is due to the Stark effect of the inter-ionic field and the observation of the width of spectral lines of which we have any exact data on their behaviour in a strong electric field will enable us to secure very important knowledge regarding the physical process during the initiation period of the spark discharge. The present paper is concerned with such an experimental study of the broadening of spectral lines of gases before the spark lines of the electrodes appear.

[1] J. W. Beams, Phys. Rev. *28*, 475; 1926.
[2] E. O. Lawrence and J. W. Beams, Phys. Rev. *32*, 478; 1928.
[3] J. W. Beams and P. N. Rhodes, Phys. Rev. *28*, 1147; 1926. G. L. Locher, J.O.S.A. *17*, 91; 1928.
[4] E. O. Lawrence and F. G. Dunnington, Phys. Rev. *35*, 396; 1930.
[5] L. v. Hámos, Naturwiss. *18*, 181; 1930.

THE EXPERIMENTAL ARRANGEMENT

The arrangement of the apparatus, as is diagramatically shown in Figs. 1a and 1b, is essentially the same as that used in the researches made by Beams,[1] Lawrence[2] and others.[3] The spark gap G which gives a succession of sparks, with a condenser C in parallel, is connected across a high tension transformer T. In order to prevent objectional oscillations in the condenser-spark gap circuit and also in the spark gap-trolley wire circuit, the water resistances, R_2 and R_2', and the stretched wire re-

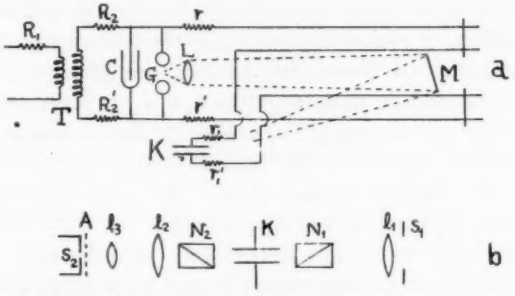

FIG. 1. *Arrangement for photographic spectra of the spark in the early stages*

sistances, r and r', of about 500 ohms of nichrome #42 are provided. Another pair of stretched wire resistances, r_1 and r_1', of about 100 ohms of nichrome #27 are also inserted in the trolley wire-Kerr cell circuit for the purpose of critically damping the oscillation. Obviously the magnitude of the resistances, r and r', must be so chosen as to make it possible to damp out the oscillations sufficiently, without delaying appreciably the closing time of the shutter and the best value could be obtained experimentally by finding the value of, r and r', which gave the minimum intensity of light passing through the Kerr cell while being careful that the other conditions remained unaltered. The value found was about 1,000 ohms and each 500 ohms were inserted in either side of the lead from the spark gap G to the Kerr cell K and it was confirmed that no oscillations could be detected with a wave-meter in the case where the resistances above determined were inserted in the circuit, while in the case where copper wires were inserted instead of the resistances, r and r', powerful oscillations corresponding to wave lengths 110m and 79m were detected according as the whole length 28m or shorter length 18m of the trolley wire was used. As a trial to investigate the damping of oscillations in the trolley wire-spark gap circuit, a Braun's tube was used after the manner de-

vised by J. Zenneck.[6] But unfortunately it was unsuccessful. To prevent any forced oscillations in the trolley circuit due to the coupling with the spark circuit, the length of lead in common between the two circuits was reduced to a minimum and the leads of both circuits were put in planes at right angles to each other.

The Kerr cell consists of parallel plates 9 cm long, 1.3 cm wide and 0.5 cm apart immersed in well purified carbon disulphide and situated between crossed nicols N_1 and N_2. The light from the central portion of the spark gap, after being condensed by the lens L and reflected by the concave mirror M of a long focal length, illuminates uniformly on the rectangular slit S_1. A convex lens l_1 focused the beam again at the centre of the cell and then the beam after passing through a convex lens l_2, a cylindrical one l_3 and an absorbing film A, was projected linearly along the slit s_3 of the spectrograph. The absorbing film A was specially prepared following the manner of the "Stufenabschwächer" by Dorgelo and it is a thin platinum film deposited on a thin glass plate by means of cathodic sputtering forming four stripes with different thickness and the width of each step was 0.8 mm respectively. In order that the light illuminate uniformly on the absorbing film and reach on the photographic plates without any obstacles, it was carefully adjusted to the relative positions of the lenses and the spectrograph.

As the operation of the apparatus has already been described in the former papers, only a brief summary will be given here. At first, the spark gap is charged up to the sparking potential which is a little higher than the opening potential of the optical shutter. Then when the spark occurs, the light from it starts down the optical path to the spectrograph; simultaneously, a collapse of potential differences starting at the gap proceeds along the trolley wires to the shutter at the velocity of light. If the light at the gap emits at the instant of the collapse of the potential across it and if the length of each of the trolley wires is made just equal to the length of the optical path, the light will arrive at the shutter just when the shutter is closing. Therefore a displacement of the slider toward the sparking gap along the trolley wires will cut out the light, while a displacement in the opposite direction will make the light pass through to the spectrograph, and this makes it possible, by a displacement of the slider, to observe the light up to any desired time after the sparking discharge takes place between the gap.

For the purpose of testing the actual operation of the system of the

[6] J. Zenneck, Ann. Phys. 7, 802; 1902.

apparatus, the following experiments were carried out with regard to the spark in open air. Making a displacement of the slider by one meter at each time along the trolley wire from its longest end, the other conditions remaining unchanged, a row of spectra, each one consisting of four stepped densities on account of being weakened by the absorbing film, was taken on the same plate. From the measurement of the photographic densities of the spectra obtained and the length of the trolley

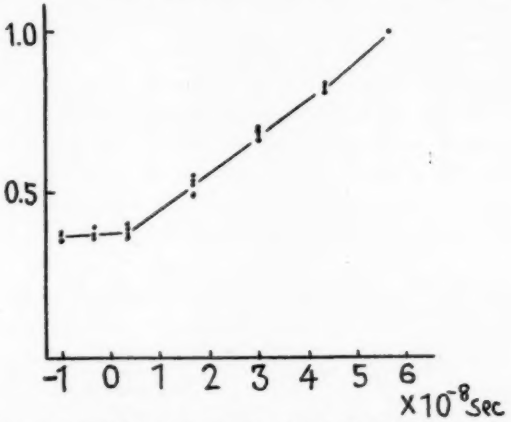

FIG. 2. *The increase of the light quantity passing through the Kerr cell as the function of time.*

wires, the relation between the total quantities of light falling on the plate and the opening durations of the shutter will be obtained as is shown in Fig 2, in which the densities were measured, for the sake of convenience, at four different wave lengths designated by I, II, III and IV in Fig. 3a and the density corresponding to the longest opening duration of the shutter was taken as unity in the ordinate while the opening duration in the abscissa was reckoned from the difference between the length of the trolley wire and the optical path. It is quite evident that the photographic density D due to the light of a definite wave length depends on the light intensity i and the duration of the exposure t and hence the variation of the density may be simply expressed by the formula,

$$\Delta D = \frac{\partial f(i, t)}{\partial i} \Delta i + \frac{\partial f(i, t)}{\partial t} \Delta t.$$

Measuring quantities ΔD, $\partial f/\partial i$, $\partial f/\partial t$ and Δt, the method of graphical integration enables us to determine the true light intensity i. But in the

case of this experiment for spark the intensity of light varies with the time and we have no means of determing $\partial f/\partial t$. The curve in Fig. 2 was

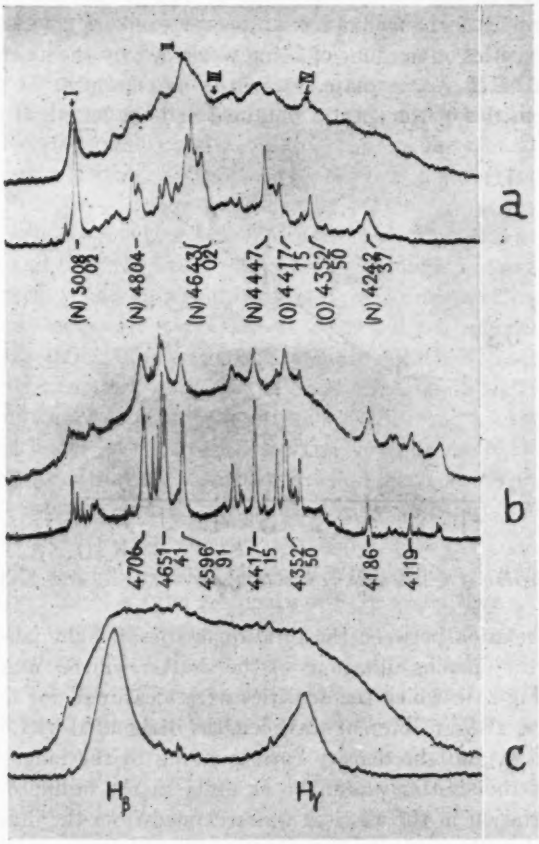

FIG. 3. *Photometric curves of the spark spectra in the early stages taken through the Kerr cell and Nicols (upper) and of the ordinary spark spectra taken without Nicols (lower). (a) air, (b) oxygen, (c) hydrogen.*

drawn taking $\partial f/\partial i$ in the place of $\partial f/\partial i+\partial f/\partial t\ \Delta t/\Delta i$ in the above formula.

It will be seen, from the curve, that the light received on the plate varies linearly with the opening duration of the shutter while some light still reaches the plate after the shutter is closed. The reason why the

Kerr cell allows light to be transmitted after the voltages of the electrodes in it are supposedly reduced to a low value may be accounted for by the remaining of some residual charges on the electrodes or the existence of some oscillations of small voltages in the circuit. But looking at the figure, especially in the positive time, it may be reliably believed that the shutter operates quite well in the manner outlined above.

THE EXPERIMENTAL RESULTS AND DISCUSSION

(*1*) *Sparks in the air.* The first experiment was concerned with observations of spectra emitted during the early stages of the spark in the air. The spark gap was made of brass spheres 15 mm in diameter and arranged 12 mm apart. The breaking potential of the initial discharge was 3.5 kv but owing to the heating of the electrodes, the succeeding sparks take place undoubtedly at less potentials than that for the initial one. The position of the concave mirror was so adjusted that the whole length of the optical path was 12.3 m.

The upper curve in Fig. 3a is the reproduction of the photometric record of the spectra taken through the shutter closing 5×10^{-8} sec after the beginning of the spark, while the lower one is of the same spectra, taken, nicols removed with the other conditions remaining unaltered. It will be seen that the two curves have little resemblance to each other and that lines in the upper extremity diffuse out with a strong continuous back-ground with the maximum intensity at about λ4600A and also that they are slightly shifted towards the red or violet side. The half breadth of only an isolated line at λλ5002, 5008A in this spectrum was estimated as about 80A.

Rectifying the current by using a kenotron inserted in the secondary circuit of the transformer and adjusting the position of the condensing lens *L*, only the light coming from immediately in front of the positive and the negative electrodes is able to pass through to the spectrograph. The results show that no metallic lines developed up to 5×10^{-8} sec after the beginning of the spark and no differences were found between the spectra in front of both electrodes.

(*2*) *Sparks in oxygen.* Oxygen gas was prepared from potassium-permanganate and dried with calcium chloride and filled at one atmospheric pressure into a glass sphere 14 cm in diameter. Spark gaps were made of a silver sphere 15 mm in diameter and put 13 mm apart in the glass sphere containing the gas. To prevent the abnormal heating of the gas, the glass sphere was cooled with air currents from an electric fan

and the old gas slowly replaced with the new gas. To avoid the objection due to the sputtering of the electrodes on the window it was necessary to wipe it off frequently.

The upper and the lower curves in Fig. 3b corresponds to those in Fig. 3a in air, the extreme diffuseness and slight shifts towards the red or the violet sides of the lines are also noticed. The great peaks in the curve correspond to the lines which were classified in the group OII by Fowler and the Stark effect of these lines had already been investigated by Böttcher and Tuczek[7] though they have obtained negative results up to the field intensity 26,000V/cm using the spectrograph of 11–16 A/mm in dispersion.

(*3*) *Sparks in hydrogen.* The experiment with hydrogen gas will be specially interesting as the gas emits only Balmer Lines whose behaviour has already been fully investigated. The same glass sphere as was used in oxygen was filled with dried hydrogen from a Kipp's apparatus. Owing to the comparatively low sparking voltage of the gas, it was necessary to insert an auxiliary gap in open air in series with the main one in the gas and then the optical shutter was operated quite well.

The upper and the lower curves shown in Fig. 3c are the reproduction of the photometric curves of the hydrogen spectra under the same conditions as stated in the case of the air spark. It will be seen that the broadening of lines H_β and H_γ are remarkable so that it seems as though they are united together into one continuous spectrum. The width of H_γ was estimated by extrapolating the photometric curve, as about 500A.

For many years the physical process of spark discharges in gas at an atmospheric pressure was considered as quite well described by the theory of Townsend. However, a serious discrepancy has arisen in recent years which has caused some workers to abandon this classical theory and the mechanism of the spark has again remained as an unsolved problem. To bring out clearly the exact nature of the spark, there are needed the exhaustive investigations of the behaviours of positive ions before and after the break down of the spark and it will be of fundamental importance to determine the potential gradient due to the space charges and the concentration of the positive ions between the electrodes. The results obtained in this experiment will serve to throw some light on the problem above mentioned.

There can be no doubt that the broadening of the spectral line is due

[7] E. Böttcher and F. Tuczek, Ann. Phys. *61*, 107; 1920.

to the Stark effect of inter-ionic fields in this case. The broadening and the shift of lines observed in the early stages of the spark may serve as a measure of the ionic electric fields. As the Stark effect of spark lines of nitrogen and of the oxygen have not yet been observed, it is to be regretted that quantitatively nothing can be deduced from the observation of the sparks in air and in oxygen, but in order to exhibit such a large broadening of the line H_γ, since it amounts to about 500A, it follows that there should exist an intense inhomogeneous inter-ionic electric field about 10^6 volts per cm which was generated in 5×10^{-8} sec after the break down of the spark and the value is in the same order of magnitude with that estimated by Beams and Dunnington in their researches on the zinc spark, which appeared at the later stage.

The knowledge of the broadening of the spectral line makes it possible also to make a rough estimation of the concentration of ions. Neglecting the Doppler and other effects due to the inter-atomic and the inter-molecular fields and assuming Holtmark's[8] formula for the width of the line due to the ionic-fields,

$$\Delta\nu = 3.25\gamma n^{2/3}\epsilon,$$

it is possible to calculate the concentration of ions n from the charge of ions ϵ, the coefficient of the Stark effect γ and the width of lines $\Delta\nu$. Taking now the value of $\Delta\nu$ corresponding to the total width 500A of the line H_γ, the value of n would be calculated as about 5.8×10^{18} per cc and thus ions amounting to 46 percent of the number of molecules at an atmospheric pressure exist. This high value of ionization is in the same order of magnitude with that estimated by Beams and Dunnington and as all effects above mentioned tend to broaden the width of the lines, this value will therefore be considered as the upper limit of ionization of the gas.

In conclusion, the writer wishes to express his indebtedness to Prof. J. Okubo for his suggestion of the problem and his advice given during the course of the experiment.

[8] J. H. Holtmark, Phys. ZS. *20*, 162; 1919.

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